Microwave path checking

by B. CHAMBERS, G8AGN*

Introduction

Although this article deals mainly with checking paths for line of sight conditions at microwave frequencies, some aspects of propagation over obstructed paths are also discussed briefly.

If the transmission path between a transmitter and a receiver is said to be "line of sight", this means that the receiver can "see" the transmitter and vice-versa. This does not necessarily imply, however, that a person standing next to the receiving antenna can literally see the transmitter, assuming that his eyesight is good enough and the atmosphere is clear and still, since, as will be shown later, a path which is obstructed at optical frequencies may be line of sight at microwave frequencies.

The significance of the path between a transmitter and a receiver being line of sight is twofold. First, even if the transmitting and receiving antennas have only modest gain, the transmitter output power required to pass a signal over a line-of-sight path which may be several hundred kilometres in length is generally only of the order of a milliwatt. Second, it is a fairly simple matter to calculate the system power budget for a given line-of-sight path and hence to estimate the probable signal-to-noise ratio at the receiver. A measurement of the actual received signal-to-noise ratio will then provide a check on the overall performance of the system. This approach is most useful since it does not rely on the amateur having access to sophisticated test equipment.

Background theory

In practice the received microwave signal will have propagated through a portion of the earth's atmosphere. Since the properties of the latter—such as pressure, temperature and humidity—vary with position, it is to be expected that its refractive index will also vary. This variation will have a marked influence on the actual path taken by the microwave signal in going from the transmitter to the receiver. Since the refractive index, n, of the earth's atmosphere has a value which is only slightly greater than unity, it is usual to work in terms of the refractivity, N, which is defined as

$$N = (n-1) \times 10^6 \qquad (1)$$

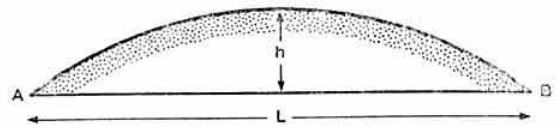

Fig 1. Microwave path over smooth earth showing earth bulge h

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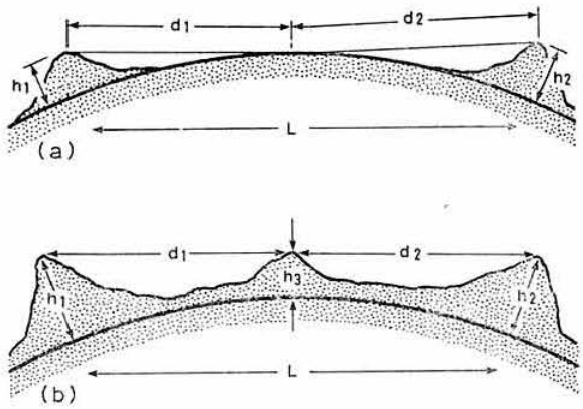

Fig 2. Preliminary path checks for line-of-sight conditions over (a) smooth earth path (b) path containing one significant obstacle

The dependence of N on pressure, temperature and humidity is apparent from

$$N = \frac{77{\cdot}6}{T} p + \frac{3{\cdot}733 \times 10^5}{T^2} e \qquad (2)$$

where p = the atmospheric pressure (mb)
e = the water vapour pressure (mb)
and T = the air temperature (°K).

The first term on the right-hand side of equation (2) corresponds approximately to the optical value of refractivity; the second term, which must be included at microwave frequencies, accounts for the presence of water vapour. Hence light waves and microwaves are affected differently in propagating through the atmosphere. Unless mixed land-sea paths are being considered, it is usual to assume that the refractive index of the atmosphere does not vary with distance along the path, and that under average propagation conditions decreases in an approximately linear manner with increasing height up to about 1km. The variation above this height is of no interest here. The effect of a decreasing refractive index with height is that, instead of propagating in a straight line, the microwave ray now follows a curved path whose radius of curvature is normally somewhat larger than the radius of the earth. For convenience the ray path between the transmitter and the receiver can again be considered to be straight if the earth is assumed to have an effective radius which is

Table 1

L (km)	h (metres) K = 1 (no atmosphere)	K = 1·17 (average optical value)	K = 1·33 (average microwave value)
5	0·5	0·42	0·38
10	2·0	1·7	1·5
15	4·4	3·8	3·3
20	7·9	6·7	5·9
25	12·3	10·4	9·2
30	17·7	15·0	13·2
35	24·0	20·5	18·0
40	31·4	26·7	23·6
50	49·0	41·8	36·8
75	110·3	94·0	82·7
100	196·1	167·2	147·1
200	784·3	668·7	588·2
300	1,764·7	1,508·3	1,326·8

different from reality. The amount by which the effective radius at a given time differs from the real radius is determined by the local variation with height of the refractive index and is best characterized by the effective earth radius factor K, where

$$K = \frac{\text{effective radius of the earth}}{\text{real radius of the earth}} \qquad (3)$$

Under abnormal propagation conditions the value of K may lie anywhere in the range 0·4 to infinity, or may even be negative; but more usually, in the UK at least, K has a value in the range 1 to 1·5 [1]. For this reason the value of 1·33($^4/_3$) is often used for average propagation conditions.

The next factor to be considered is that of the curvature of the earth. Fig 1 shows the two ends A and B of a microwave path which are separated by a distance L. The height, h, of the earth bulge at the midpoint of the path may be calculated from

$$h\,(\text{metres}) = \frac{L^2\,(\text{km})}{51K} \qquad (4)$$

(Imperial unit equivalents to the equations are given in the appendix). Table 1 shows the magnitude of h for path lengths up to 300km and for three values of K.

It can be seen from Table 1 that the effective height of the earth bulge decreases as the value of K increases, and vice-versa. Values of K greater than 1·33 correspond to above-average microwave propagation conditions, and if the value of K becomes infinite or negative then the condition known as ducting occurs when the earth is effectively flat. Also from Table 1 it would appear that for *normal* values of K the smooth earth can be assumed to be flat for path lengths less than about 20km. If the path length is longer than this then it is advisable to make a preliminary check for possible line-of-sight conditions before taking the trouble to construct a detailed ground-profile diagram. The preliminary check consists of assuming that the earth between the transmitter and the receiver sites is smooth as shown in Fig 2(a) and calculating the sum of the distances d_1, d_2 to the horizon from each end of the path. If this total distance ($d_1 + d_2$) is greater than the path length L then the path *may* possibly be line of sight. The distance, d, to the horizon

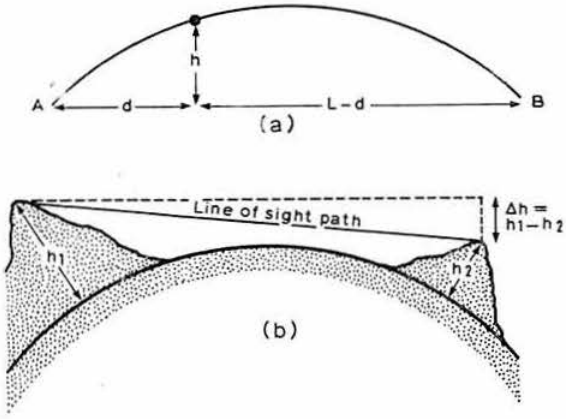

Fig 3. Geometry of parabolic arc profile diagram

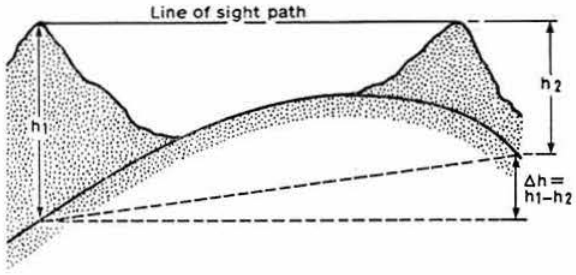

Fig 4. Tilted parabolic arc profile diagram

from the top of a hill which is of height h may be found from

$$d\ (\text{km}) = 3{\cdot}57\sqrt{K\,h\,(\text{metres})} \qquad (5)$$

Table 2 gives values of d for various values of h and K.

If the ground profile between the transmitter and receiver sites can be assumed to contain only a single significant feature, as shown in Fig 2(b), then the preliminary check can be modified to include this. Under these conditions the path *may* be line of sight if

$$L > 3{\cdot}57\ \sqrt{K(h_1 - h_3)} + 3{\cdot}57\ \sqrt{K(h_2 - h_3)} \qquad (6)$$

For a more detailed path check it is necessary to draw a ground-profile diagram. This is essentially a side elevation or ground section of the path between the transmitter and the receiver which is drawn with the vertical or height scale greatly exaggerated in comparison to the horizontal or distance scale. The smooth circular earth profile would then be depicted as a portion of an ellipse. This is difficult to construct for an arbitrary path length but, fortunately, because the vertical scale on the diagram is greatly exaggerated the elliptical arc can be approximated very closely by a parabolic arc which is rather simpler to construct. Fig 3(a) shows a parabolic arc representation of the surface of a smooth earth between a transmitter and a receiver. The height h of the earth bulge at a distance d from end A of the path is given by

$$h\,(\text{metres}) = \frac{d\,(L - d)}{12{\cdot}74\,K} \qquad (7)$$

where L and d are in kilometres and L is the path length.

When the heights h_1 and h_2 above sea level of the transmitter and receiver are added to the diagram, as shown in Fig 3(b), it can be seen that the line-of-sight path is, in general, not horizontal since h_1 and h_2 usually are not the same. If desired, an additional term can be added to the right-hand side of equation (7) to tilt the ground profile

Table 2

h (metres)	Distance to horizon d (km)		
	K = 1	K = 1·17	K = 1·33
100	35·7	38·7	41·1
200	50·5	54·7	58·2
300	61·8	67·0	71·3
400	71·4	77·3	82·3
500	79·8	86·5	92·1
1,000	112·9	122·3	130·2
3,000	195·5	211·8	225·5

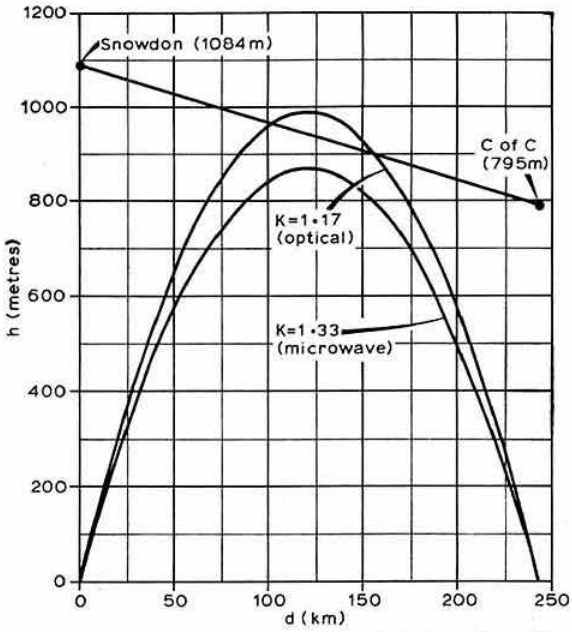

Fig 5. Parabolic arc profile diagram for path between Snowdon and the Cairnsmore of Carsphern

diagram so that the line-of-sight path is horizontal. Then h is given by

$$h\ (\text{metres}) = \frac{d\,(L - d)}{12{\cdot}74\ K} + \frac{d\,(h_1 - h_2)}{L} \qquad (8)$$

and the resulting ground profile diagram is as shown in Fig 4.

Practical examples

The use of equations (7) and (8) is best illustrated by some examples of real paths. Consider first the path between Snowdon (1,084m asl) and the Cairnsmore of Carsphern (795m asl) which is mainly over the sea and is approximately 243km in length. Using equation (7), values of h in metres are calculated at 20km increments of d. The results are given in Table 3 and are plotted in Fig 5 for K values of 1·17 and 1·33, corresponding to the average optical and microwave cases respectively. It can be seen from Fig 5 that the path at the midpoint is obstructed at optical frequencies by an earth bulge some 50m in height. At microwave frequencies, however, the minimum path clearance is approximately 65m. Before the path can be positively classified as line of sight, the frequency of the transmitter must be specified and one further check made; this will be discussed after a further example, illustrating the use of equation (8), has been given.

The second path to be considered is that over land between Merryton Low (488m asl, 7km NE of Leek) and Cleeve Hill (329m asl, 5km NE of Cheltenham), a distance of 136km. Values of h calculated from equation (8) for path increments of 10km and two values of K are given in Table 4 and plotted in Fig 6. It can be seen from the figure that if the earth were smooth then the path would certainly be line of sight for both values of K. Since the path is overland, however, the height of the ground above sea level must be

Table 3

d (km)	h (metres) K = 1·17	K = 1·33
0	0	0
20	298·5	262·6
40	543·4	478·1
60	734·8	646·4
80	872·5	767·6
100	956·9	841·8
120	987·7	869·0
140	965·0	850·0
160	888·7	781·8
180	758·8	667·6
200	575·4	506·3
220	338·6	298·0
240	48·2	42·4
243	0	0

superimposed on top of the smooth-earth (ie sea level) profiles already plotted to obtain the actual ground clearance. In practice it is rarely necessary to draw the complete ground profile since a glance at the appropriate map will usually be sufficient to identify the critical points along the path. Normally this can be done using maps with a scale of 1: 250,000 but in cases of doubt the larger scale 1 : 50,000 maps should be used. Along the path being considered here, the critical point occurs at a distance of about 80km from Merryton Low. At this point, in the vicinity of Birmingham, the ground rises to a height of at least 150m, which is sufficient to obstruct the path even under normal microwave propagation conditions. Hence it is probable that this particular path is never line of sight.

Fresnel Zone clearance

In the preceding paragraphs it has been assumed that a path which is not actually obstructed by a closely spaced obstacle is line of sight. In practice this is not necessarily the case since the microwave signal does not propagate from the transmitter to the receiver as a single ray but as a cone of rays. The received signal has contributions from a number of these rays, and the magnitude of the former will depend on the relative phase of these contributions. Thus an obstacle such as a hill situated near to the line-of-sight ray may block some of the contributing rays and lead to a decrease in received signal. It is usually assumed that the obstacle will have negligible effect on the received signal level if it is situated more than a certain distance away from the line-of-sight ray, as shown in Fig 7. This minimum distance is

Table 4

d (km)	h (metres) K = 1·17	K = 1·33
0	0	0
10	96·2	86·1
20	179·0	160·3
30	248·1	222·8
40	304·4	273·4
50	346·9	312·2
60	376·1	339·3
70	391·8	354·5
80	394·1	357·9
90	383·0	349·6
100	358·4	329·4
110	320·5	297·4
120	269·1	253·6
130	204·3	198·0
136	159·0	159·0

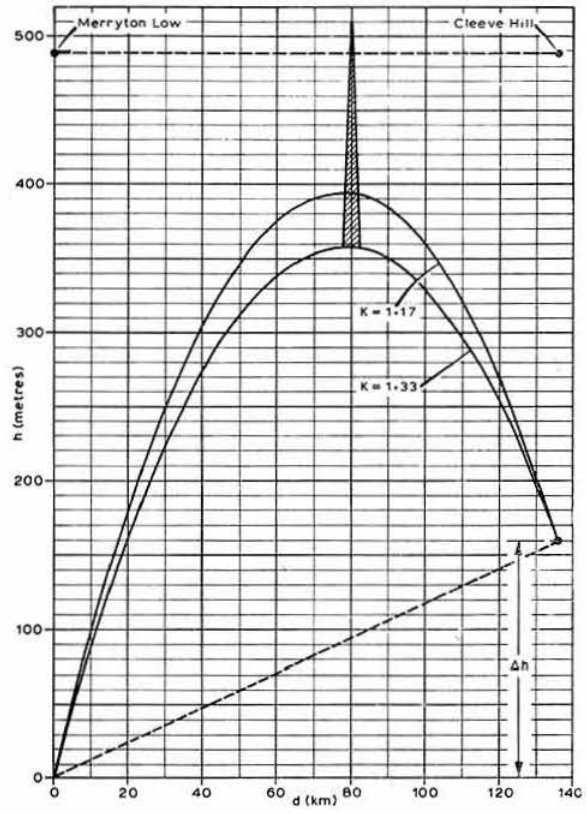

Fig 6. Tilted parabolic arc profile diagram for path between Merryton Low and Cleeve Hill

normally taken to be 0·6 of the first Fresnel Zone (often denoted as F_1), or

$$S_{min}\,(\text{metres}) > 0{\cdot}6F = 329\sqrt{\frac{d_1\,d_2}{(d_1 + d_2)\,f}} \qquad (9)$$

where d_1, d_2 are in kilometres and are the distances from each end of the path to the point under consideration, and f is in megahertz. To illustrate the use of equation (9) examine again the 243km sea path considered previously. It was found that the minimum path clearance of the line-of-sight ray was approximately 65m for K = 1·33. If the path is to be considered as truly line of sight then the value of S_{min} must be less than this figure at the frequency of interest. Using equation (9) and letting d_1 = 135km, d_2 = 108km gives S_{min} = 43·4m for f = 3·45GHz, and S_{min} = 25·5m for f = 10GHz. Hence the path is truly line of sight at these frequencies for K = 1·33.

If an obstacle is closer to the line-of-sight ray than the distance S_{min}, or the line-of-sight ray is actually obstructed, then the strength of the received signal will be diminished. To obtain an estimate of the additional path loss due to the obstacle in this case, it is often assumed that the latter can be replaced by a simple knife-edge whose diffraction loss properties are well known. Fig 8 shows the diffraction loss for a knife-edge obstacle as a function of the clearance, S,

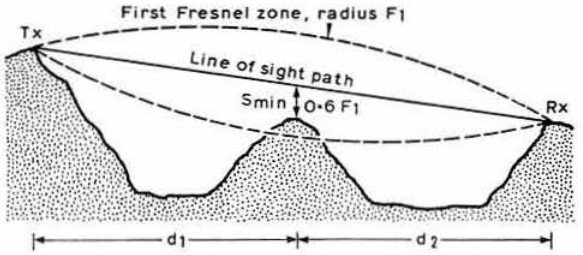

Fig 7. Fresnel Zone surrounding line-of-sight ray on a microwave path

of the line-of-sight ray. It can be seen now why the value of S_{min} was chosen to be $0{\cdot}6F_1$ since this corresponds to the case of no diffraction loss. Note also that when the obstacle just touches the line-of-sight ray (S = 0) the diffraction loss is 6dB.

To return to the second path example, the ground obstruction for K = 1·33 was found to be approximately 20m at a distance of 80km from Merryton Low. At this distance, using equation (7) modified to calculate F_1 rather than $0{\cdot}6F_1$, $S/F_1 = -0{\cdot}37$ for a frequency of 3·45GHz and $S/F_1 = -0{\cdot}64$ for a frequency of 10GHz. Hence from Fig 8 the additional path loss due to diffraction when K = 1·33 may be estimated as 11dB at 3·45GHz and 14dB at 10GHz. It should be emphasized that these estimates are probably on the conservative side since the ground obstruction at microwave frequencies may well consist in practice of a number of obstacles each with its own diffraction loss. The treatment of multiple obstacle diffraction, although fairly straightforward, is outside the scope of this article. Further details can be found elsewhere [2].

If a given path is found to be obstructed, transmission losses due to obstacles other than hills, such as trees, hedges and buildings, may also have to be taken into account. It is difficult to quote definitive values for these losses since they will depend not only on frequency but also, more importantly on the water content of the obstacle in question. As a rough

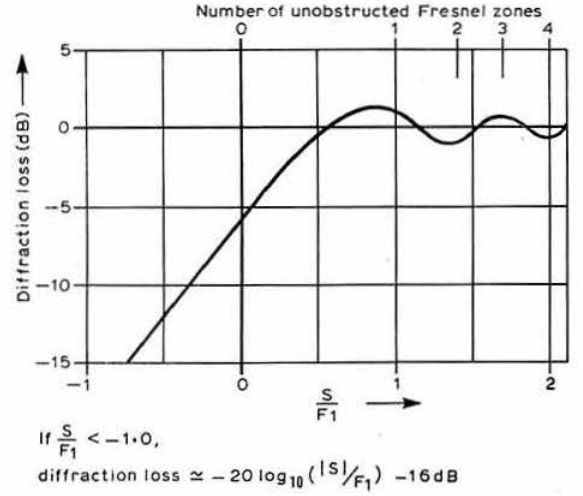

Fig 8. Diffraction loss due to a knife-edge obstacle

guide, measurements made at a frequency of 3·3GHz [3] have suggested that the following should normally be regarded as opaque to microwaves:

(a) rows of trees in leaf, if more than two in depth;
(b) trunks of trees, whether leafless or in leaf;
(c) walls of masonry, if more than 20cm in thickness;
(d) any but the lightest wooden buildings, particularly if containing partitions.

In spite of these rather gloomy conclusions and their implications for propagation across an urban environment, it should be pointed out that in the author's experience 3·4GHz signals have been received through hedges and individual trees in leaf and in one case over a 1km path through a housing estate, the transmitting and receiving antennas being inside houses on opposite sides of a hill some 30m high. The lesson to be learned from this test is clear; even if on paper a particular path is not line of sight it is still possible, on occasion, to transmit signals over it, as other propagation effects such as diffraction, scattering or ducting may come to the rescue. Herein lies the challenge and fascination of amateur radio at microwave frequencies.

References

[1] "The radio refractive index gradient over the British Isles", by J. A. Lane. *J Atmos Terrestrial Phys*, 1961, Vol 21, pp 157–166.

[2] "Multiple knife-edge diffraction of microwaves", by J. Deygout. *IEEE Trans on Ant & Prop*, 1966, AP14, pp 480–489.

[3] "Some experiments on the propagation over land of radiation of 9·2cm wavelength, especially on the effect of obstacles", by J. M. McPetrie and L. H. Ford. *J IEE*, 1946, 93 IIIA, pp 531–538.

Appendix

Imperial Unit equivalents of equations (4)–(9)

$$h_{feet} = \frac{L^2}{1{\cdot}5K}, \text{ L in miles} \quad (4)$$

$$d \text{ miles} = 1{\cdot}22\sqrt{K\,h_{feet}} \quad (5)$$

$$L > 1{\cdot}22\sqrt{K(h_1 - h_3)} + 1{\cdot}22\sqrt{K(h_2 - h_3)} \quad (6)$$

L in miles; h_1, h_2, h_3 in feet

$$h_{feet} = \frac{d\,(L - d)}{1{\cdot}5K} \quad d, L \text{ in miles} \quad (7)$$

$$h_{feet} = \frac{d\,(L - d)}{1{\cdot}5K} + \frac{d\,(h_1 - h_2)}{L} \quad (8)$$

d, L in miles; h_1, h_2 in feet

$$S_{min}\,(\text{feet}) > 1369\sqrt{\frac{d_1 d_2}{(d_1 + d_2)\,f}} \quad (9)$$

d_1,d_2 in miles, f in megahertz

Some meteorological aspects of the anomalous propagation of radio waves

by E. R. Thomas*

RADIO transmissions within the vhf/uhf bands (30–3,000MHz) are often directional and line of sight so that the horizon is about the limit for useful transmissions. At these frequencies radio waves passing upwards through the atmosphere are lost into space; that is, they are not reflected by the ionosphere as are radio waves of lower frequency, and for this reason vhf/uhf transmissions are beamed more or less horizontally. Unlike longer waves the whole of the path length of vhf/uhf transmissions is in the troposphere, which is the layer of air extending from the earth's surface up to about 11km (35,000ft)—in European latitudes—and is the region within which clouds, rain and weather occur.

Propagation of the vhf/uhf radio waves through the troposphere is greatly influenced by refraction, which is the change of direction, or gradual bending, to which energy waves (radio, light, sound) are subject on passing through a medium of varying density or electrical properties. The refraction of waves passing through air is probably better described by reference to light waves, which are visible, rather than to radio waves which are not.

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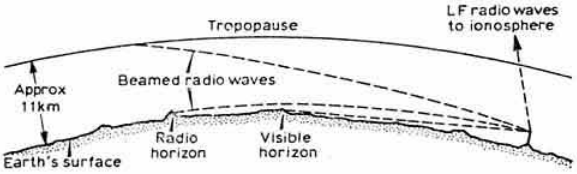

Fig 1. Transmission paths of radio waves

Visual refraction

Mirages are examples of the influence of abnormal refraction in the layers of air close to the earth's surface. They are the result of large vertical temperature gradients which considerably affect the air density in the vertical, and are of two main classes. The most common is the "inferior" mirage which is seen over flat strongly-heated surfaces, eg desert or road surfaces. This mirage produces the illusion of an expanse, or pools, of water. In this case the eye, looking more or less horizontally, sees objects well above the horizon as the light waves are refracted away from the earth's surface (Fig 2), and the apparent expanse of water is really a view of the sky.